Seeking Single Top Quarks at D0

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Abstract

You are: single, non-smoking and produced via the electroweak interaction. We are: 600 physicists interested in having fun and in measuring $V_{tb}$for the first time. We know you are out there somewhere, please contact us through our 5000 ton mutual friend.

The top quark was discovered in 1995. Physicists are now studying its properties in detail at the Fermilab Tevatron, just outside Chicago. Until recently, we have observed only top quark pair production via the strong interaction. However, the Standard Model of particle physics also predicts the production of single top quarks via the electroweak interaction. This mechanism gives us our first chance at a direct measurement of V_{tb}, and the best sample in which to study spin polarization effects in quarks. If only we could find it! Well, there is hope! The D0 experiment has recently announced first evidence of single top quark production. After introducing the D0 experiment and motivating our interest in single top quarks, I'll present the status of our recent efforts to find this elusive signal.

1 Introduction to Particle Physics

Particle physics describes, at the smallest distance scales, what the world is made of and how the fundamental components interact. The quest for a definitive list of fundamental natural "elements" has lasted thousands of years, but has stabilized over the last 30 due to the Standard Model of Particle Physics. In this model, ordinary matter is made up of different arrangements of up-quark, down-quarks and electrons. Various other exotic matter particles are also considered fundamental but are either only produced in high energy interactions, or are present in nature but very difficult to detect. A complete list of known fundamental particles is given in Figure 1. The right-column of this figure also includes the force-carrying bosons. These particles are responsible for propagating the known interactions between matter particles: the EM force, the strong nuclear force and the weak nuclear force. It should be noted that the 4th known force, gravity, is very weak and is not described by the Standard Model.

Since the initial development of the Standard Model, particle physicists have been struggling to disprove it, to no avail. Despite known incomplete aspects of the model such as: more than 20 free parameters, the lack of an explanation for gravity and unnatural mathematical coincidences, the Standard Model has proven to be one of the most successful models in all of science. Particle physicists continue to search for new particles (not already included in Figure 1), to do precision measurements of the known particles and to measure carefully the relationships between particles of the Standard Model. This lecture deals with the first measurement of a specific free-parameter

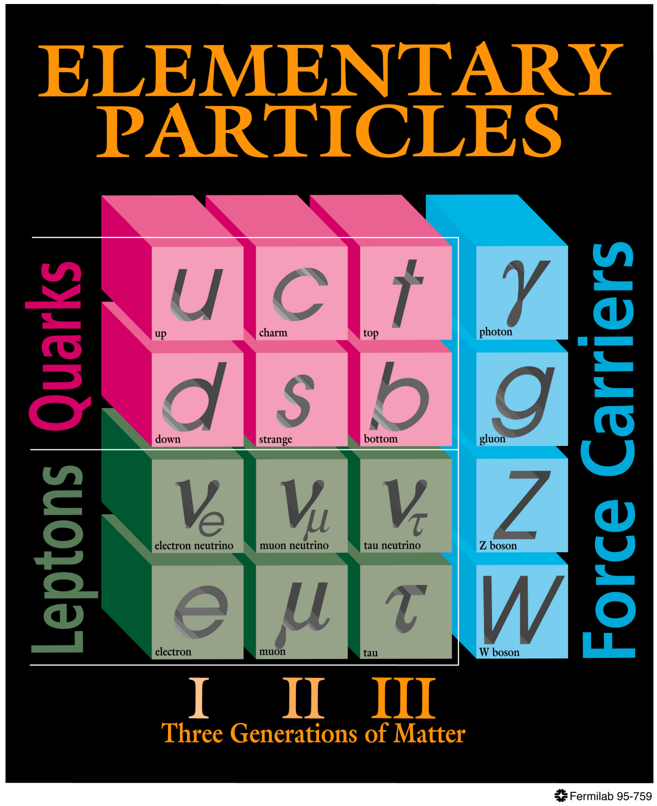

Figure 1: The particles of the Standard Model.

of the Standard Model which describes the relationship between the top-quark, the b-quark and the W-boson: V_{tb}.

2 The DØ Experiment

The Fermilab Tevatron is currently the world's highest energy particle collider, providing 1.96 TeV proton-antiproton collisions to two experiments: CDF and DØ . Figure 2 shows an aerial view of the Tevatron, which is located near Chicago, Illinois. The DØ experiment is based around a large multi-purpose detector which is shown in cartoon in Figure 2. The detector is designed to detect the signatures of electrons, muons, jets (manifestations of quarks, or gluons) and taus and also to distinguish between various particle types. DØ is specifically noted for its excellent energy resolution (calorimetry) and angular coverage of the muon system.

The DØ experiment is run by a collaboration of more than 600 physicists from 19 countries. The collaboration has existed since the early 1980s and the first incarnation of the detector took data starting in 1992. However, the current DØ experiment has been taking data since only 2001. In the last 5 years it has accumulated more than 10 times the data which had been accumulated in previous running. This large data-set has allowed DØ physicists to make new measurements and to improve precision on existing measurements.

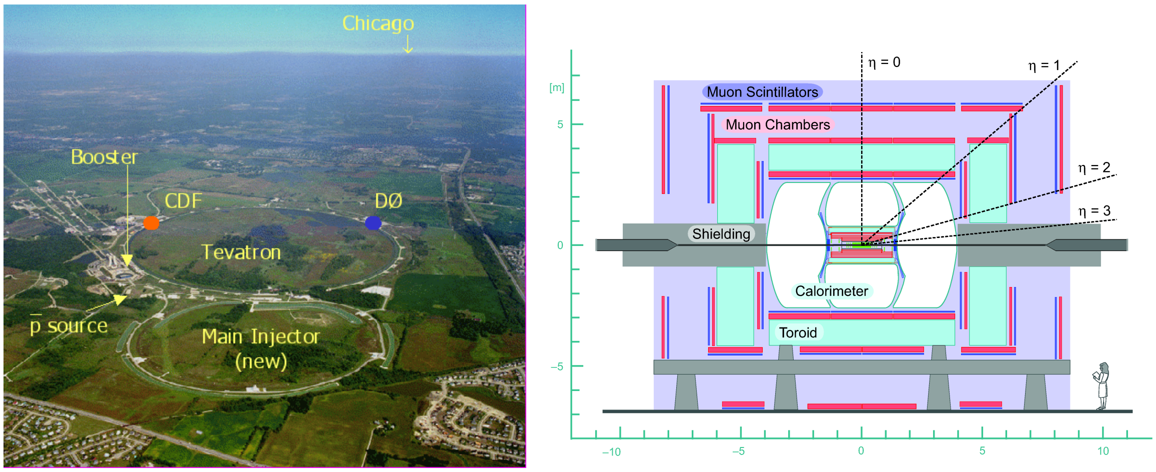

Figure 2: The left-side shows an aerial view of the Fermilab Tevatron. On the right is a cartoon-view of the DØ detector.

3 Top Quark Physics and Single Top

The top quark was discovered at the Tevatron in 1995. It is the heaviest known fundamental particle with a mass similar to that of an atom of gold. Because it is so much more massive than the other quarks, it has long been thought to play a special role in the Standard Model. Measuring the properties of the top quark is currently an exciting area of research.

Until now, all top quark events studied in the lab have been produced via in pairs via the strong interaction. These samples of top quarks have allowed many properties of the top quark to be explored in detail as can be seen in Figure 3.

While top pair production is the dominant mechanism for top quark production at the Tevatron, it is also possible to produce single top quarks via the electroweak interaction. Two diagrams for "single top" production are shown in Figure 4. The so-called s-channel production (left) results in a top quark and a b quark in the final state. t-channel production (right) results in an extra quark in the final state. Observation of either of these processes would be a world-first. It would also allow the first direct measurement of V_{tb}, which will be described in some detail later.

Another motivation for measuring the production of single top quarks is the search for physics beyond the Standard Model. It turns out that s-channel and t-channel single top production rates (cross-sections) are each sensitive to different sources of new physics. The plot in Figure 5 shows the t-channel cross section plotted vs. the s-channel cross-section. The solid circle is the expected Standard Model value in this plane. This figure shows that some new-physics contributions will express themselves as an increase in the t-channel cross-section without changing the s-channel rate and vice versa. The two Feynman diagrams included in this figure show a process which would bias the s-channel measurement (heavy-W production or charged Higgs production) and one which would bias only the t-channel measurement (flavour-changing neutral currents).

Figure 6 shows, on a log scale, the relative production rates of various processes at the Tevatron. It can be seen that the total rate of these two single top processes is only about a factor of 2 less than that of top pair production, which has been a known process for more than

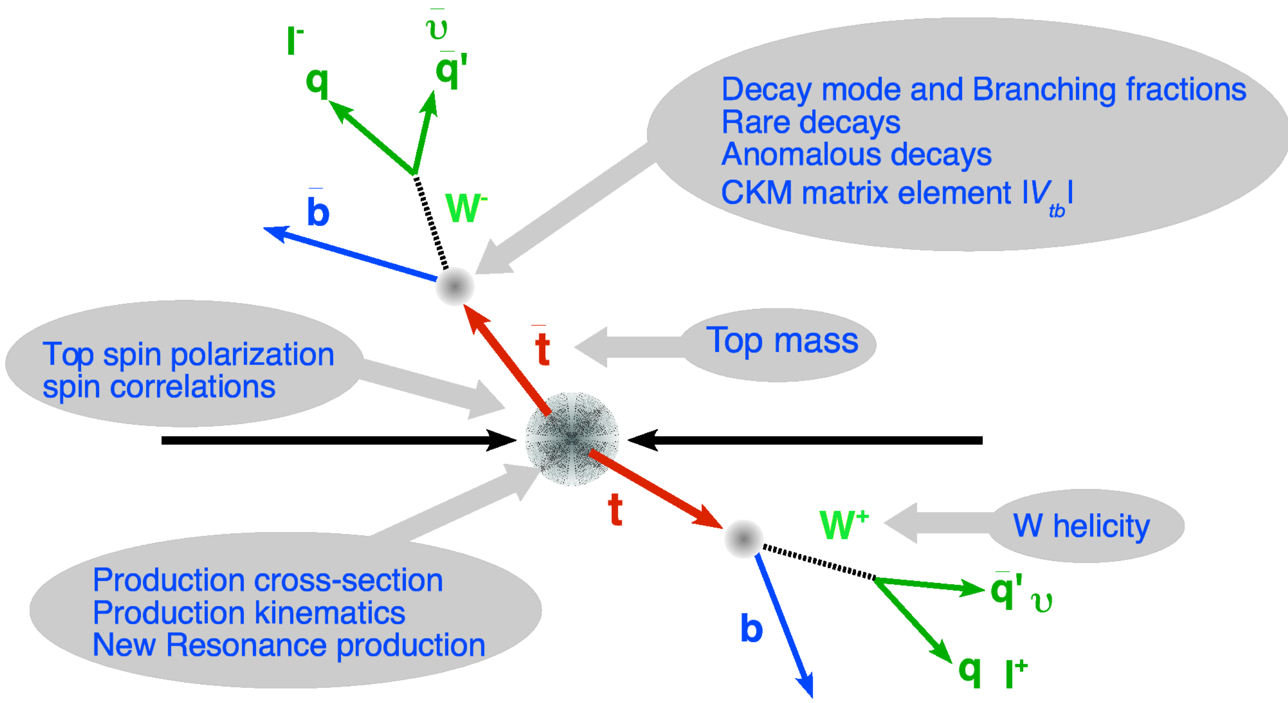

Figure 3: Artist's rendering of top quark pair production. Labels indicate the types of measurements that can be performed from each part of the production and decay.

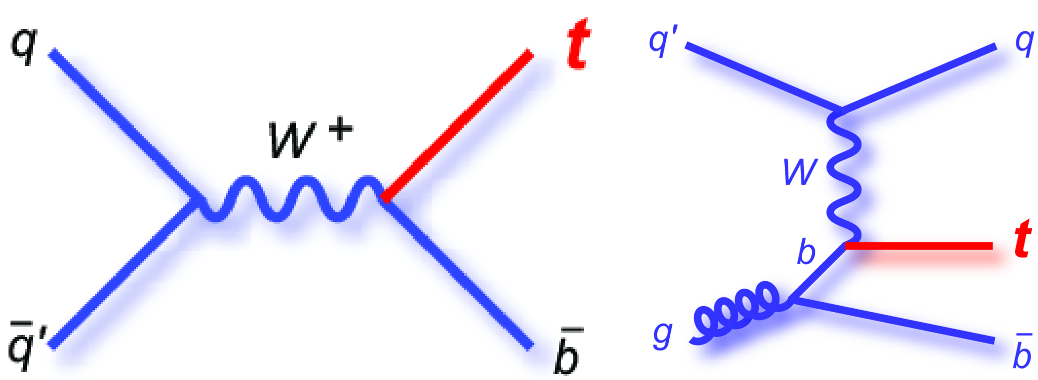

Figure 4: Feynman diagrams representing the most important contributions to single top production at the Fermilab Tevatron. The left-side diagram is referred to as s-channel single top production while the right-side is referred to as t-channel production.

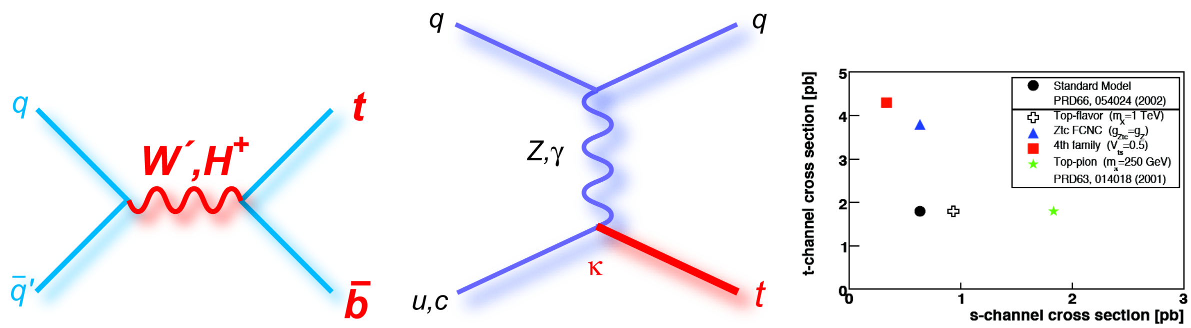

Figure 5: Sources of "new physics" and their potential influence on the measured single top cross section. The two Feynman diagrams represent exotic processes which could enhance the single top cross section. The right-most plot illustrates how different exotic processes can influence the measured s-channel or the measured t-channel cross section independently.

10 years. However, the troublesome issue is that the signature for single top quark production is less distinct than that for pair production. In particular, it is much more difficult to distinguish W+jet production from single top quark signatures than it is to distinguish it from top pair production. A consequence of this is that physicists must adopt sophisticated analysis techniques to separate the single top signal from an otherwise overwhelming background.

4 Modeling the Background

Since this is an attempt to find a very small signal amidst a large background of known Standard Model processes, it is important to have an excellent understanding of the background in order to be convinced any new signal is real. To that end, the vast bulk of the time taken to perform an analysis of this type is spent building and verifying a background model. In this analysis, most background were modelled using Monte Carlo simulations while some were taken from independent data sources. Figure 7 shows distributions comparing data to background model for four different kinematic variables. In each case the data is plotted as a black circle and our estimate of each background is represented by a different colour. It can be seen that the data points are in good agreement with the sum of the background distributions. The "contamination" from the signal (blue) is very small, unfortunately. More than 2000 of these distributions were carefully checked before this analysis was allowed to proceed to the measurement stage.

5 Decision Trees

The distributions in Figure 7 illustrate that signal appears as a small contamination on a large background. It should be noted that at this stage several background-reducing selections have already been applied. A common way to proceed would be to find more variables which can distinguish between signal and background and make more and more rigorous selections until the signal content is sufficiently enhanced. The left-side of Figure 8 illustrates a nearly ideal situation in which a single variable distribution provides excellent separation between signal and

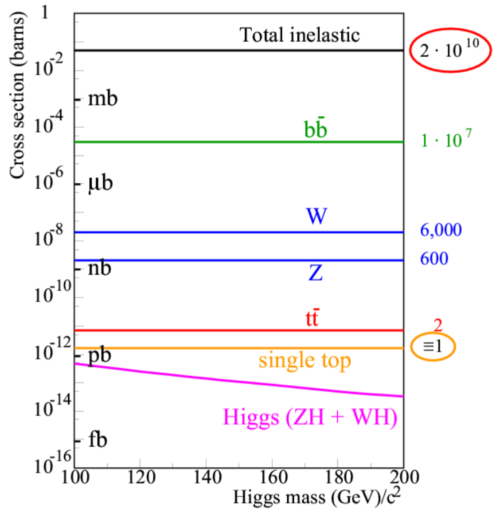

Figure 6: Relative rates of interesting processes at the Fermilab Tevatron. The vertical scale on the left is in terms of cross section, the scale on the right represents the relative rate normalized to single top quark production.

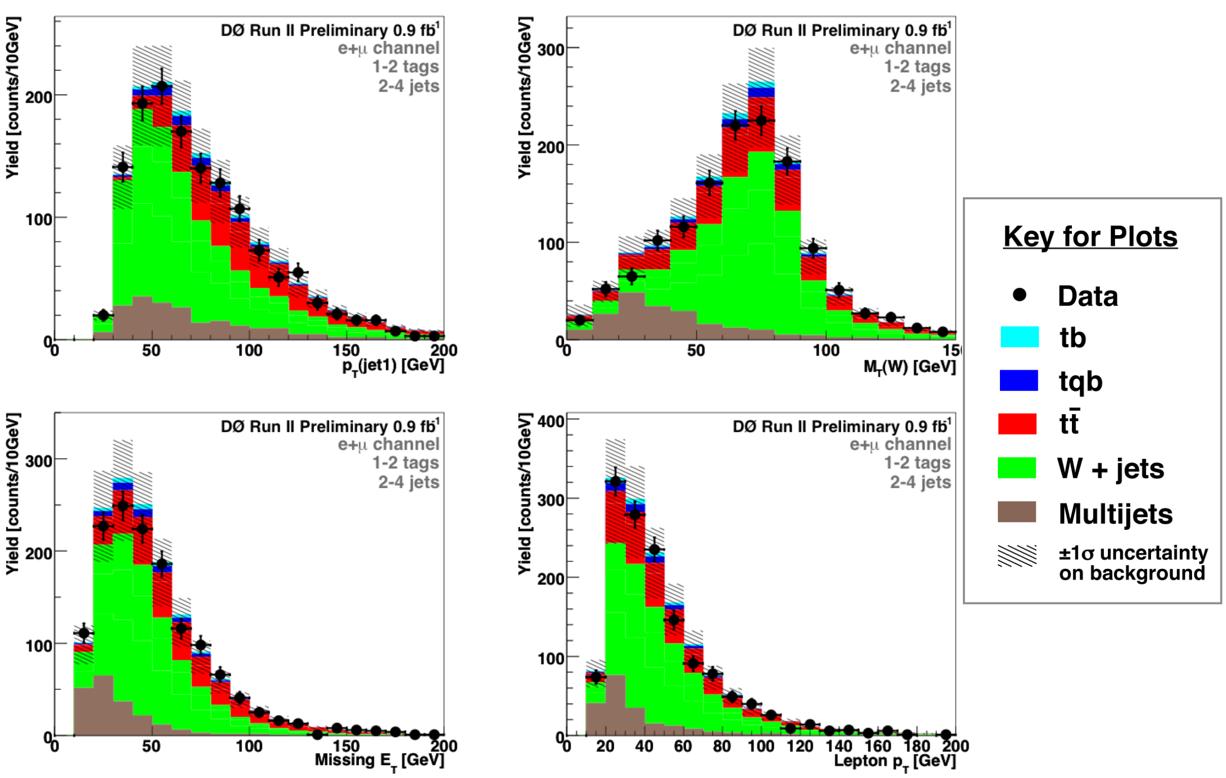

Figure 7: Data and background overlays for 4 different kinematic distributions. Reading clockwise from the top left corner: the transverse momentum of the highest transverse momentum jet in each event, the reconstructed W transverse mass, the missing transverse energy and the transverse momentum of the lepton produced in top decay.

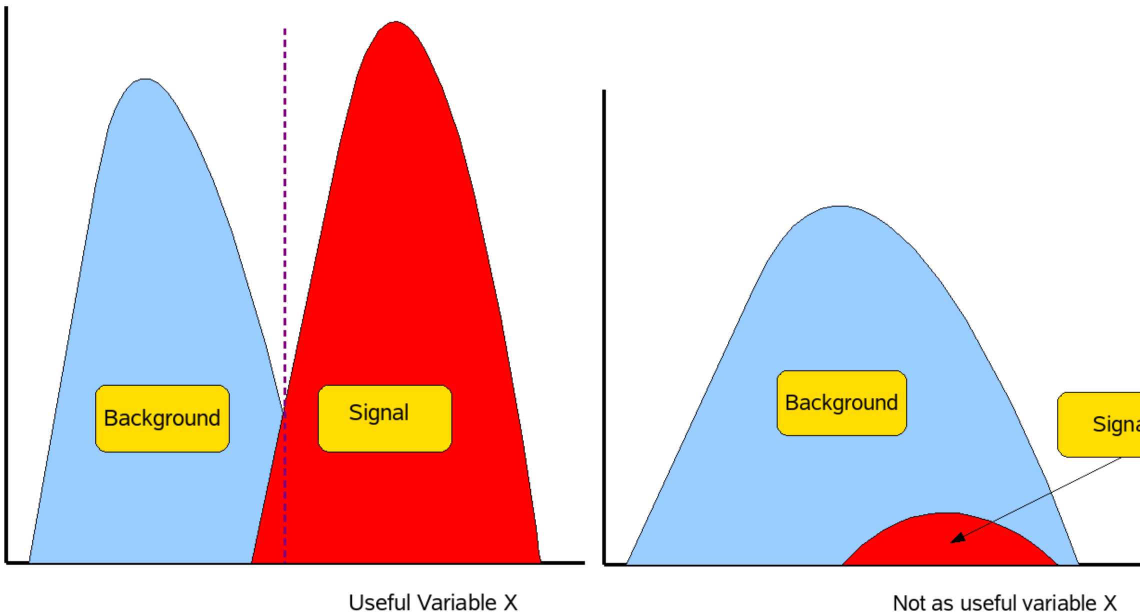

Figure 8: Signal and background distributions in (left) and idealized case and (right) a more realistic case.

background. Even in the idealized case, making a selection by placing a vertical line on this distribution and classifying events to the right as signal and events to the left as background is prone to error. Some background seeps into the signal region and, worse, some precious signal is lost in the background region. Unfortunately, the single top search is far from the idealized case. The situation resembles the more closely the right side of Figure 8. In other words, there is far more background than signal and the separation between the two is minimal. Clearly, attempting to extract the signal via a series of sequential selections on variables like this is far from optimal.

Any successful analysis of this data-set must therefore rely on a multivariate technique: a technique which combines many variables into a single, enhanced, classifier. One such technique is known as a decision tree. A decision tree is an algorithm "trained" on samples of simulated signal and background which can then be applied to detector data and an independent background simulation. The algorithm combines any number of weak variables into a single enhanced discriminant. An example of a basic decision tree is shown on the left side of Figure 9. The blue ovals in this figure are referred to as "nodes". The decision tree algorithm is applied recursively at each node. In this case, all variables have been sorted and the one called H_T has been determined to have the most discriminating power and so has been chosen to start the tree. The "signal-like" events then move along the "pass" line and are subjected to further selection (next the M_T selection is applied). The "background-like" events are not ignored however, they also have further selections applied (next is the P_T selection). This process continues until a "leaf" of the tree is reached. This stopping point occurs when either no improvement in signal-to-background ratio can be achieved or when not enough data remains to continue growing the tree. The purity of each leaf, how much signal and how much background is present, is known for this simulated data-set. This purity value is the output of the decision tree for each event. After

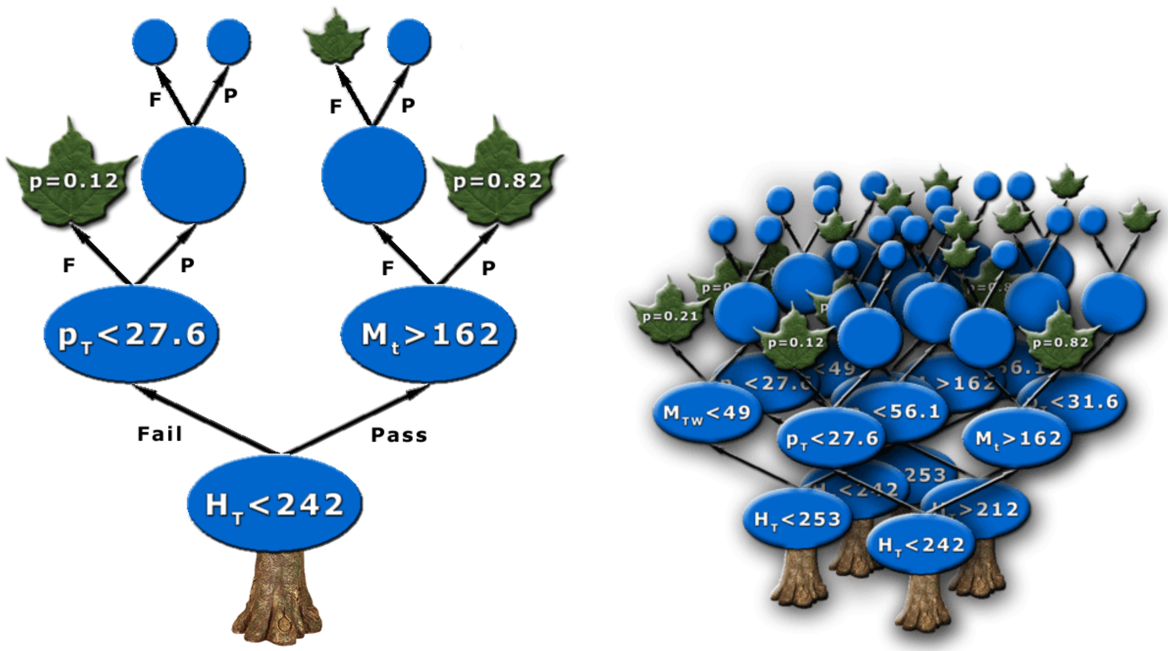

Figure 9: Artist's rendering of a single decision tree (left) and a boosted forest of decision trees (right).

this optimal tree has been grown on simulated data it is applied to real data and an independent set of simulated background events. Each real-data event then follows the branches of the tree and ends-up in a specific leaf and is therefore assigned a specific purity value. The distribution of purity values is the new discriminating variable, signal will be pushed to the right side of this distribution (high purity) and background will be pushed to the left (low purity).

The separation of signal and background can be further enhanced by "boosting" the decision tree. This involves growing a forest of decision trees. Each new tree that is grown is re-optimized on the type of signal events which the previous tree had the most difficulty identifying. Once a forest is grown then the tree outputs are averaged is a specific way to make a new discriminant which is superior to that of any of the individual trees.

The sketch in Figure 10 shows signal efficiency vs. background efficiency. Ideally, whatever method is chosen for the analysis would sit in the upper left corner of this plot where signal is maximized and background is minimized. It can be seen in this illustration that a decision tree is expected to perform significantly better than a cut-based analysis (sequential selection criteria) and should give similar performance to a neural network. However, boosting the decision tree provides a further performance enhancement. The results of this analysis are consistent with this rough sketch.

5.1 Ensembles

Once the optimal procedure for extracting the signal has been established, it must be tested to ensure it does not bring bias to the measure of the single top cross section. This can be done

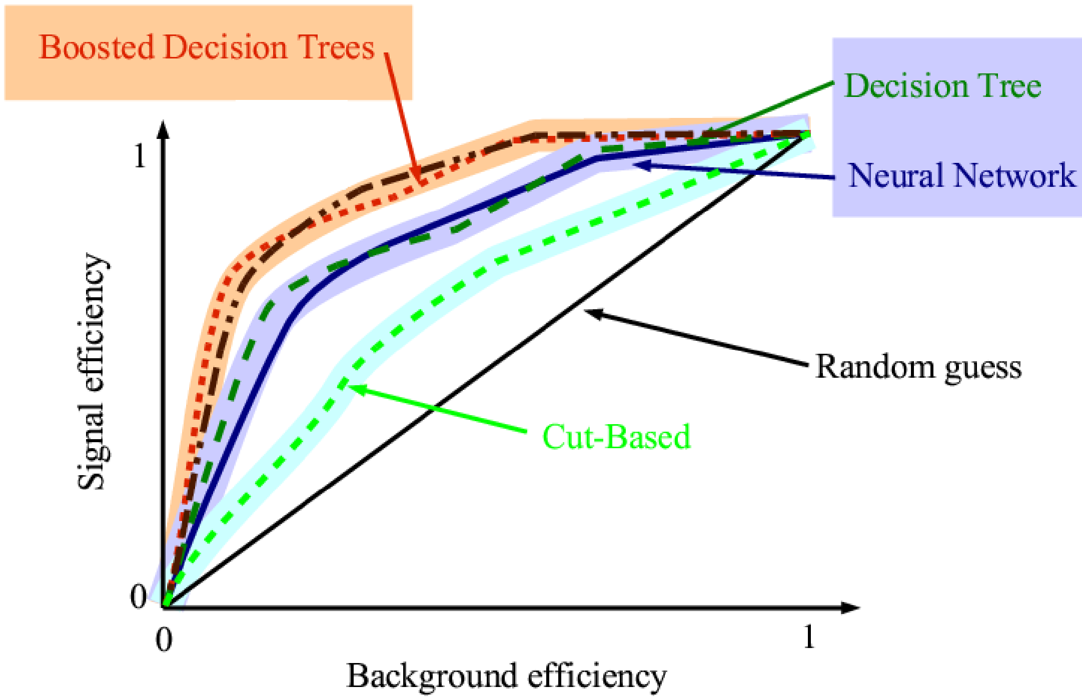

Figure 10: Sketch of expected performances of various multivariate techniques.

through ensemble tests. 10s of thousands of fake DØ experiments were run in simulation with varying amounts of single top signal added to the background model. The amount of signal ranged from 0 to the Standard Model expected cross section to 3 times the expected cross section. The algorithm to extract signal (boosted decision trees) and the cross section measurement software was applied to each pseudo-experiment. The cross section returned was statistically consistent with the known input cross section in every case, validating the method.

5.2 Sensitivity

The sensitivity in this analysis is also defined using ensembles of pseudo experiments. Nearly 70,000 pseudo-experiments were created with 0 signal content and were analyzed. The sensitivity is defined by the fraction of those pseudo experiments which, through fluctuations, gave a measured cross section of at least the Standard Model value. This fraction is 1.9%, corresponding to 2.1 standard deviations in a Gaussian distribution.

6 Measuring Cross Section and V_{tb}

6.1 Cross Section and Significance

It should now be possible to measure the cross section, assuming there is a significant signal to measure in data. The measurement technique used in this analysis builds a Bayesian posterior probability density function as shown in Figure 11. The peak of this distribution gives the single

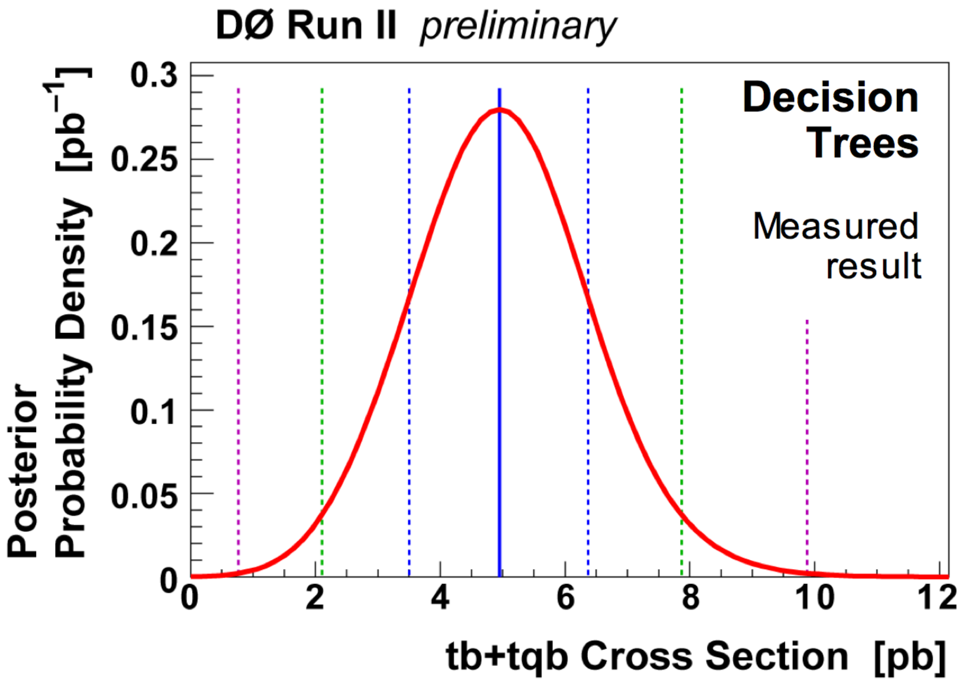

Figure 11: Measured posterior probability density function resulting from the boosted decision tree analysis.

top cross section and the width represents the error. It yields 4.9 ± 1.4pb.

The procedure to measure the significance is the same as the one used to measure the expected sensitivity. The fraction of pseudo-datasets in the 0-signal ensemble which has at least the measured cross section is 0.035%, which corresponds to a 3.4 standard deviation excess and first evidence of single top quark production.

6.2 Measuring V_{tb}

The CKM matrix describes the mixing of quark generations. In other words, the probability that any quark will transition to another is parameterized in the elements of a non-diagonal matrix. One element of this matrix which has never been directly measured is V_{tb}. Single top quark production provides the first opportunity to measure V_{tb}, since the cross section quoted in the previous section is directly proportional to $|V_{tb}|^2$. This means that a measurement of $|V_{tb}|^2$ can be made using the same infrastructure used to measure the cross section with addition of some extra sources of theoretical error. Performing this measurement yields $0.68 < |V_{tb}| < 1$ at 95% confidence.

7 Summary

More than 10 years after the discovery of top quark pairs, first evidence of single top quarks produced via the electroweak interaction has been found. This challenging search required a

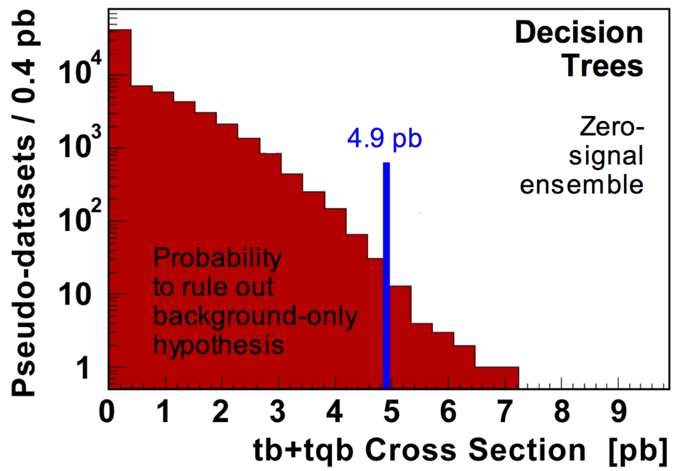

Figure 12: The measured cross section from more than 68000 pseudo-experiments in which zero signal is present. Pseudo-experiments to the right of the blue line have a measured cross section of at least the measured value.

detailed understanding of other Standard Model background processes and the use of a novel multivariate technique: boosted decision trees. This has allowed the first measurement of both the single top cross section and the CKM matrix element V_{tb}. The results are consistent with the Standard Model.